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Full Scale Tests of Water Mist Fire Suppression Systems for Navy Shipboard Machinery Spaces: Part II - Obstructed Spaces

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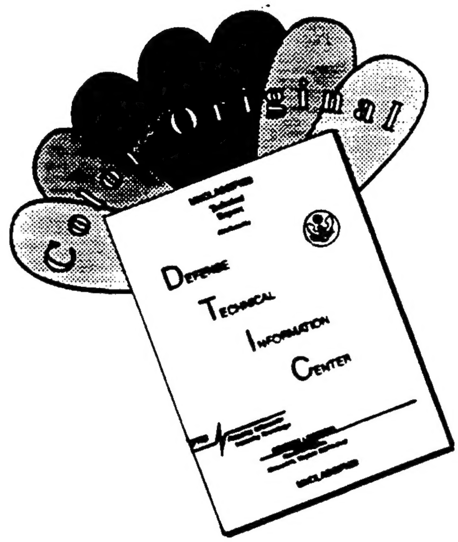

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The Phase II tests were conducted in a simulated machinery space on the Navy's fire test ship, the ex-USS *Shadwell*. It was the same space as used in the Phase I tests except that it was fitted with mockups of equipment to further evaluate the firefighting capabilities of the water mist system in a more realistic machinery space environment. The fire threats were a combination of spray and pan fires in the range of 2.5 to 7.5 MW. Five different types of spray nozzles were evaluated. Initially, the nozzles were installed in the overhead at one level as in the Phase I study. Then, to improve the performance of the system, the nozzles were installed on two levels as is the practice with Halon systems. With the best system, all of the fires were extinguished in less than 25 seconds, using less than 100ℓ (25 gallons) of water.

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FULL SCALE TESTS OF WATER MIST FIRE SUPPRESSION SYSTEMS FOR NAVY SHIPBOARD MACHINERY SPACES: PHASE II - OBSTRUCTED SPACES

1.0 BACKGROUND

The U.S. Navy is conducting an ongoing investigation into the use of water mist as a replacement for Halon 1301 total flooding systems which are currently installed in shipboard machinery spaces. Intermediate scale tests have demonstrated the potential capabilities and benefits of water mist technologies for machinery space applications [1]. In addition, full scale tests have been conducted in a simulated machinery space aboard the ex-USS SHADWELL in Mobile, Alabama, as follows:

Phase I - These tests were conducted in any empty, i.e., unobstructed machinery space with the candidate water mist nozzles installed at one level, high in the overhead of the space. The primary objective of these tests was to verify the results of the intermediate scale tests and identify any concerns associated with scaling these preliminary results to full scale applications. The Phase I tests demonstrated the potential ability of water mist to extinguish both shielded and unshielded Class B fires in full scale, relatively uncluttered, machinery space applications. Also observed during these tests was a rapid reduction in the temperature of the space almost immediately after mist system activation. This reduction in temperature will aid in manual intervention, minimize thermal damage, and may prevent fire spread beyond the space. The results of these tests also demonstrate the differences in firefighting capabilities of the candidate water mist systems. While these results are extremely encouraging, it was recognized that modifications to each system would be needed to shorten the extinguishment times and minimize potential fire damage. These modifications were included in the second phase of this investigation.

Phase II - These tests were conducted in the Phase I machinery space which was fitted with mockups of equipment to further evaluate the firefighting capabilities of the candidate water mist systems in a more realistic machinery space environment. Initially, the nozzles were installed at one level in the overhead of the space as in the Phase I study. Then, in an attempt to improve the performance of the candidate systems, the nozzles were installed on two levels as is the practice with the current Halon 1301 total flooding systems.

This report addresses the results of the Phase II tests conducted in accordance with the approved test plan [2]. The Phase I results were covered in a separate report [3].

Manuscript approved January 23, 1996.

2.0 OBJECTIVE

The objective of this program was to develop an environmentally acceptable replacement for Halon 1301 for new ships, starting with LPD-17 (Fig. 1). Water mist is particularly attractive for this application since, unlike Halon 1301, water has zero ozone depletion potential, zero global warming potential, is non-toxic, non-corrosive and has tremendous cooling capacity.

This evaluation focussed primarily on the firefighting capabilities of the "state of the art" water mist technologies as applied to machinery space applications. An assessment of water mist system design parameters (i.e., flow rates, nozzle spacings, nozzle location (i.e., single versus multilevel systems), etc.) was also conducted to optimize the firefighting capabilities of each system as well as to add robustness to the system's performance.

3.0 WATER MIST OVERVIEW

3.1 Background

In general, the efficiency of a particular water mist system is strongly dependent on the system's ability to not only generate sufficiently small droplet sizes, but to distribute "critical concentrations" of droplets throughout the compartment. It is worth remarking that a widely accepted "critical concentration" of water droplets required to extinguish a fire is yet to be determined. Factors that contribute to the distribution of this critical concentration of water mist throughout the compartment consist of droplet size, velocity, the spray pattern geometry as well as the momentum and mixing characteristics of the spray jet, and the geometry and other characteristics of the protected area. Hence, water mist must be evaluated in the context of a system rather than as an extinguishing agent.

3.2 Current Water Mist Technologies

There are currently over twenty manufacturers of water mist hardware, some of which are commercially available as fire suppression systems while others are still under development or being used in other applications. For the purpose of more general discussion, these candidate systems can be broken down into three distinct categories: single-fluid low-pressure, single-fluid high-pressure, and twin-fluid systems. The droplet size distributions produced by similar technologies fall into discrete ranges. These ranges are shown as the volumetric mean droplet diameters (D_{V50}) in Fig. 2 All three system categories have been demonstrated as effective fire suppression technologies [1]. A brief description of the three general categories is given in the following paragraphs.

3.2.1 Single-fluid Low-pressure Systems

Single-fluid low-pressure systems operate at or below 12 bar (175 psi). Because of this relatively low operating pressure, these systems often utilize the same piping and materials as conventional sprinkler systems. This translates into a relatively simple, lower cost system. The lower pressure nozzles also utilize larger orifice sizes to produce the same water flow rates. This increased orifice size is less susceptible to clogging and can be an advantage in reducing the need for corrosion prevention and water supply filtration (to some extent).

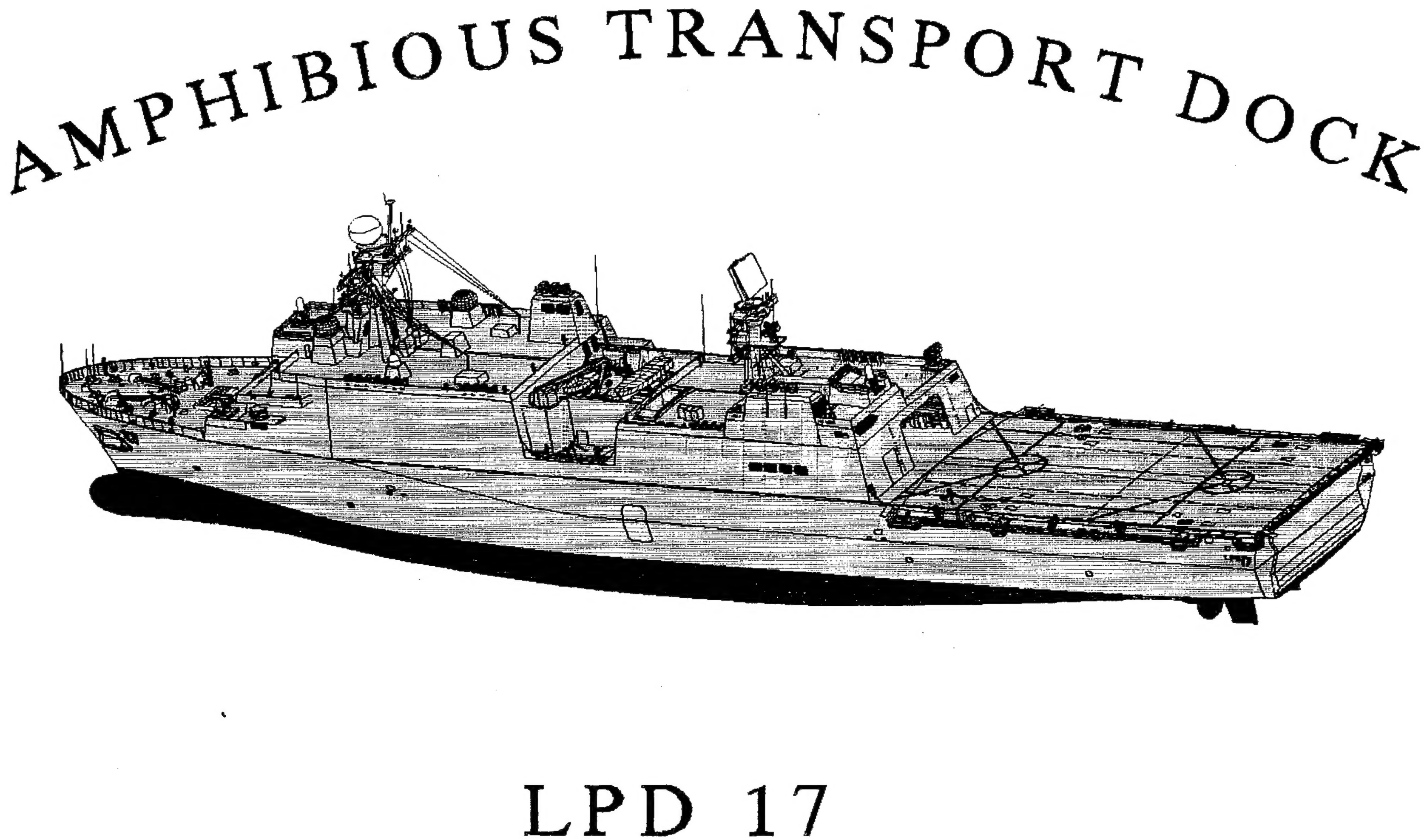


Fig. 1 - Conceptual Drawing of LPD-17

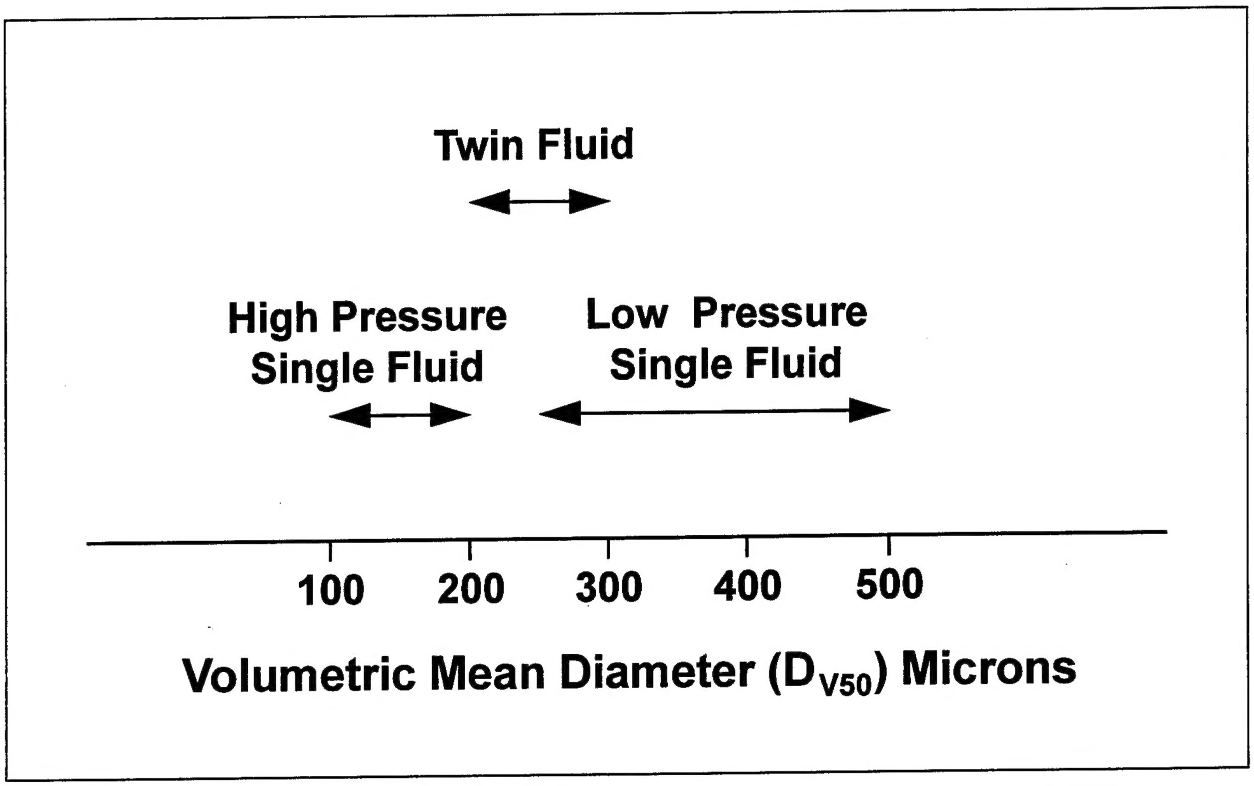


Fig. 2 – Droplet size comparison

The disadvantages of these systems are larger average droplet sizes and higher water flow rates. The larger droplets have a higher terminal velocity than smaller droplets due to the mass of water contained in the droplet. This results in a higher fall out rate of droplets from the mist. This fall out significantly reduces the amount of mist that effectively mixes throughout the space, especially in higher elevations and around obstructions. Consequently, these larger droplet sizes reduce the systems' capabilities against obstructed/shielded fires. The low pressure systems also utilize higher water flow rates in an attempt to negate these increased fall out losses.

3.2.2 Single-fluid High-pressure Systems

The single-fluid high-pressure systems, to date, have proven to be the most effective fire extinguishing mist system technology. The single-fluid high-pressure systems operate at pressures up to 210 bar (3000 psi). These high operating pressures provide an effective means of generating high concentrations of small droplets. The smaller droplet sizes exhibit more gaseous-like behavior and superior mixing characteristics. These characteristics increase the systems' capabilities against shielded/obstructed fires. The smaller droplets also have superior heat transfer characteristics due to greater surface area to volume ratios. This allows the high pressure systems to utilize water more efficiently and consequently use less water.

The disadvantage of these systems is an increased cost due to the need for high-pressure system components (i.e., pipes, fittings, valves, pumps, etc.). The power requirements associated with the high-pressure pumps may, in many cases, also prove to be a severe disadvantage.

3.2.3 Twin-fluid Systems

Twin-fluid systems require two fluids, water and an atomizing fluid, both being supplied to the nozzle using separate piping networks. These nozzles utilize a high velocity stream of air or nitrogen to shear the water into small droplets. This process usually takes place in or directly in front of the nozzle. One advantage of this technology is that it produces large quantities of small water droplets at low operating pressures, usually less than 7 bar (100 psi). The disadvantage of this technology is the additional piping, storage volume, and associated cost of the atomizing fluid.

3.3 Candidate Nozzles

Four commercially available water mist fire suppression systems and one generic system, produced using off-the-shelf industrial spray nozzles, were selected for this evaluation based on the intermediate scale tests [1]. The candidate systems cover the range from low to high pressure single-fluid systems. Twin fluid systems were not included in this evaluation due to the results of the intermediate scale tests (average performance) and due to the difficulty of running two pipes to each nozzle. The generic nozzles were evaluated to identify any variations in performance between the "state of the art" water mist technologies and ad hoc systems with similar droplet size distributions and water usage rates. The commercially available systems were evaluated at the manufacturer's recommended design parameters (i.e., pressure and flow rate, but not nozzle spacing). The systems evaluated during this test series include Baumac MicroMist, Grinnell AquaMist, a generic system produced using modified Spraying Systems nozzles, and two Marioff Hi-fog nozzles. The candidate nozzles are shown in Fig. 3. A brief description of each system is as follows:

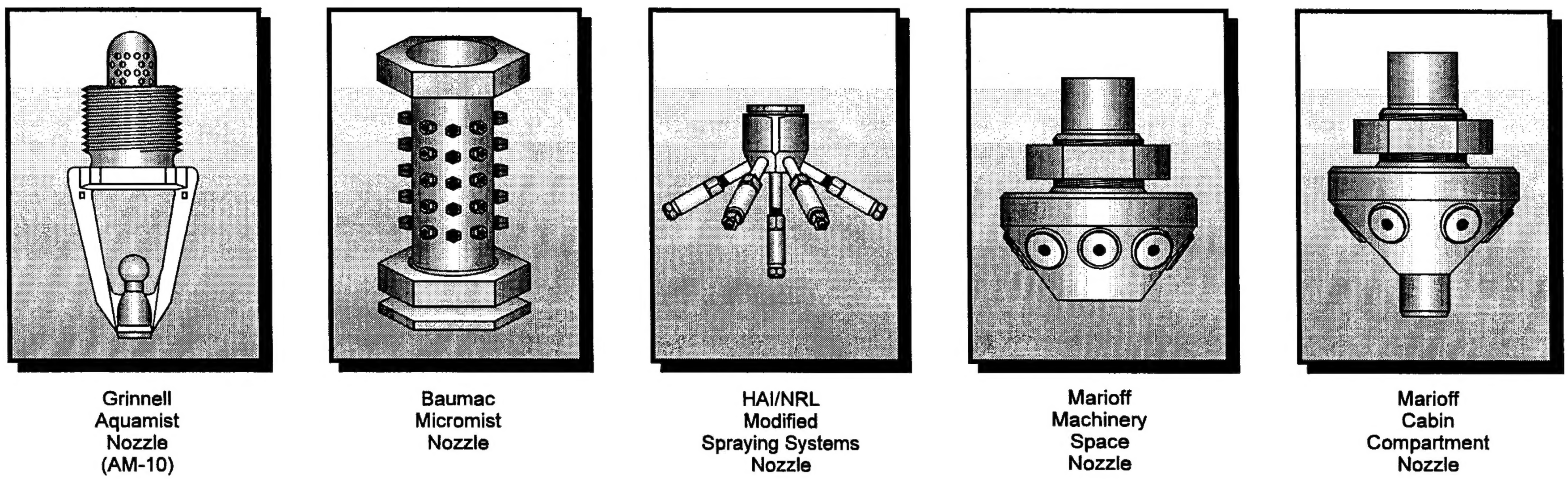


Fig. 3 – Candidate water mist nozzles

3.3.1 Baumac MicroMist System

The Baumac MicroMist system was custom designed for this test series. The Baumac system is a single-fluid, high-pressure system which was evaluated at an operating pressure of 70 bar (1000 psi). The Baumac nozzle consisted of 40 smaller nozzles configured in five rows of eight nozzles installed 45° apart in 2.5 cm (1 in.) stainless steel tubing (Fig. 3). Four smaller nozzle types/sizes (MX-8, MX-12, MX-15, and MX-20) were installed in this nozzle body and were varied during these tests. In its original configuration (all MX-8 nozzles), the nozzle has a nominal k-factor of 0.45 Lpm/bar$^{1/2}$ (0.03 gpm(psi$^{1/2}$)). The system was evaluated using a 2.4 m (8.0 ft) nozzle spacing with two nozzles installed at each nozzle location. This corresponds to a water mist application rate of 1.3 Lpm/m^2 (0.03 gpm/ft^2).

3.3.2 Grinnell AquaMist System (AM-10)

The Grinnell AquaMist system is a single-fluid, low-pressure system which has a operating pressure of 12 bar (175 psi) and is similar to a standard automatic sprinkler system in terms of system hardware and operating principles. The system produces small droplets by impinging a water stream on a spherical deflector plate. The relatively low-pressure AquaMist system substitutes efficiency in producing small droplets (produces larger droplets than the high-pressure nozzle) for the cost and commercial advantages of using standard hardware (hardware used by conventional sprinkler systems). The nozzle recommended for this evaluation (AM-10) has a nominal k-factor of 3.5 Lpm/bar^{½} (0.26 gpm/psi^{½}) and is typically installed with a 2.0 m (6.5 ft) nozzle spacing. During these tests, the nozzles were installed in the fire compartment with just over a 2.0 m (6.5 ft) nozzle spacing which corresponds to a mist application rate of 3.0 Lpm/m^2 (0.075 gpm/ft^2).

3.3.3 Marioff Hi-fog System

The Marioff Hi-fog system is a high-pressure single-fluid system which has an operating pressure of 210 bar (3000 psi), the highest pressure of any commercially available water mist system. This system produces small droplets with high momentum. Two Marioff nozzles were selected for this evaluation: a residential cabin nozzle (Model Hf-S05) and a machinery space nozzle (Hf-S09). The Marioff's machinery space nozzle contains nine orifices, three central orifices surrounded by six perimeter orifices. The nozzle has a k-factor of 1.2 Lpm/bar^{½} (0.08 gpm/psi^{½}) and has a recommended nozzle spacing of 2.0 m (6.5 ft). During these tests, the nozzles were installed in the fire compartment with a 2.0 m (6.5 ft) nozzle spacing which corresponds to a mist application rate of 3.0 Lpm/m^2 (0.07 gpm/ft^2). The Marioff's cabin nozzle contains five orifices, one central orifice surrounded by four perimeter orifices. The nozzle has a k-factor of 0.65 Lpm/bar$^{1/2}$ (0.04 gpm/psi$^{1/2}$) and, when installed in a residential cabin, has a recommended nozzle spacing of 3.0 m (10.0 ft). During these tests, the nozzles were installed in the fire compartment with a 2.0 m (6.5 ft) nozzle spacing which corresponds to a mist application rate of 1.6 Lpm/m^2 (0.039 gpm/ft^2). The cabin nozzle was selected for the bilevel installation based on its low flow rate and its demonstrated firefighting capabilities [1]. The machinery space nozzle was evaluated in the single level installation only due to its relatively high flow rate.

3.3.4 Modified Spraying Systems 7N Nozzle

The modified Spraying Systems nozzle is a single-fluid, high-pressure nozzle which was evaluated at a pressure of 70 bar (1000 psi). The nozzle body is comprised of a Spraying Systems Model 7N nozzle body with seven model 1/4LN nozzles installed on 7.6 cm (3 in.) long brass nipples. The six 1/4LN nozzles installed around the perimeter are Model 1/4LN4, and the one in the center is a Model 1/4LN8. The purpose of varying the size of these nozzles was to produce droplets of different size and momentum: the perimeter nozzles produce small droplets with low momentum, and the center nozzles produce larger droplets with high momentum which serves to mix the mist throughout the space. In this configuration, the nozzle has a k-factor of 1.1 Lpm/bar^{½} (0.08 gpm/psi^{½}). These nozzles were installed with a 2.4 m (8.0 ft) nozzle spacing, which corresponds to a mist application rate of 1.6 Lpm/m^2 (0.04 gpm/ft^2).

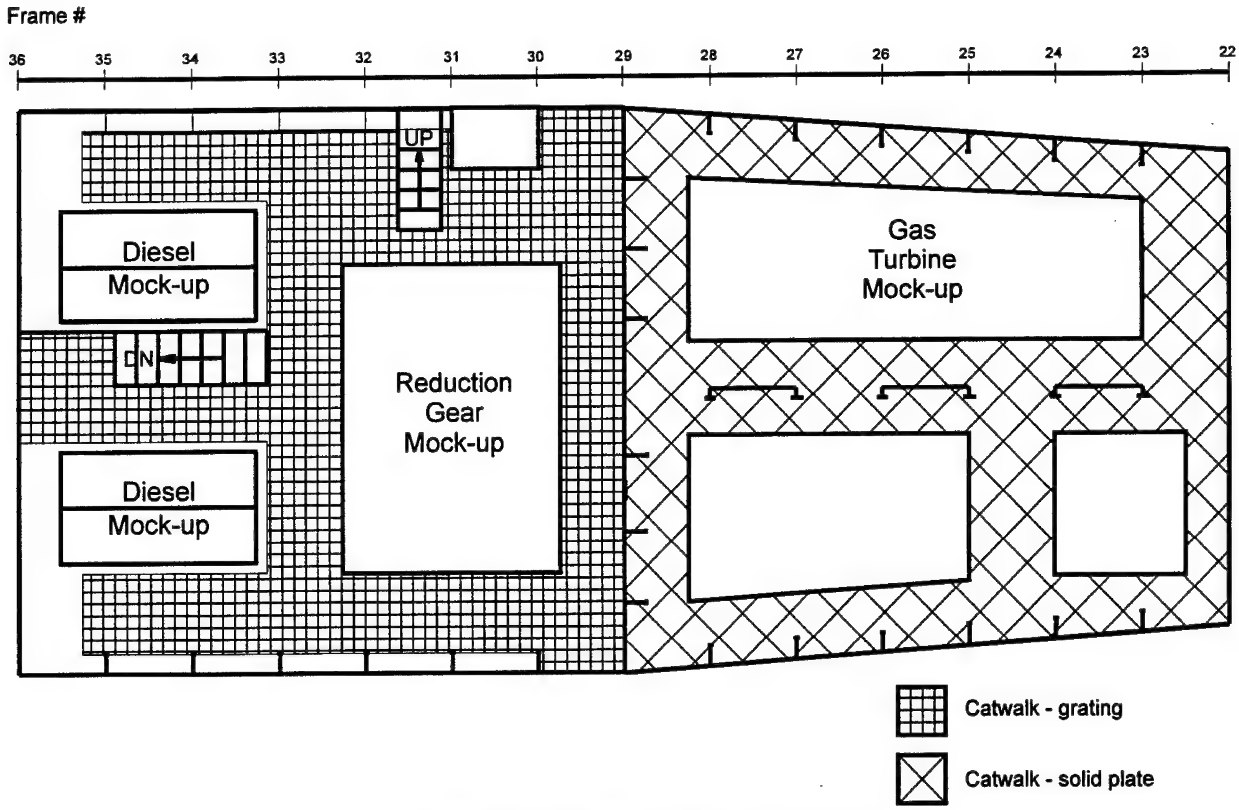
3.3.5 Modifications Made to the Systems Between Test Series

In an attempt to increase the fighting capabilities of the candidate systems, many of the system parameters were varied between Phase I and Phase II of this test program. The Baumac nozzles were reoriented (installed horizontally instead of vertically) in an attempt to increase the downward spray momentum. The Baumac system was also operated at a higher nozzle pressure (105 bar versus 95 bar (1500 psi versus 1350 psi)) in the second phase of this investigation. The Grinnell AquaMist system was also evaluated at a higher pressure, i.e., 18 bar versus 14 bar (250 psi vs. 210 psi), during the Phase II series in an attempt to reduce the droplet size and increase the spray momentum characteristic of the system. Marioff Hi-fog decided to change the nozzle recommended for this application. For a single level nozzle installation, Marioff recommended their machinery space nozzle, and for the bilevel installation, they recommended their residential cabin nozzle. The modified Spraying Systems nozzles were also evaluated at a higher pressure, i.e., 100 bar versus 70 bar (1500 psi versus 1000 psi) in an attempt to increase the mist dispersion characteristics of the system.

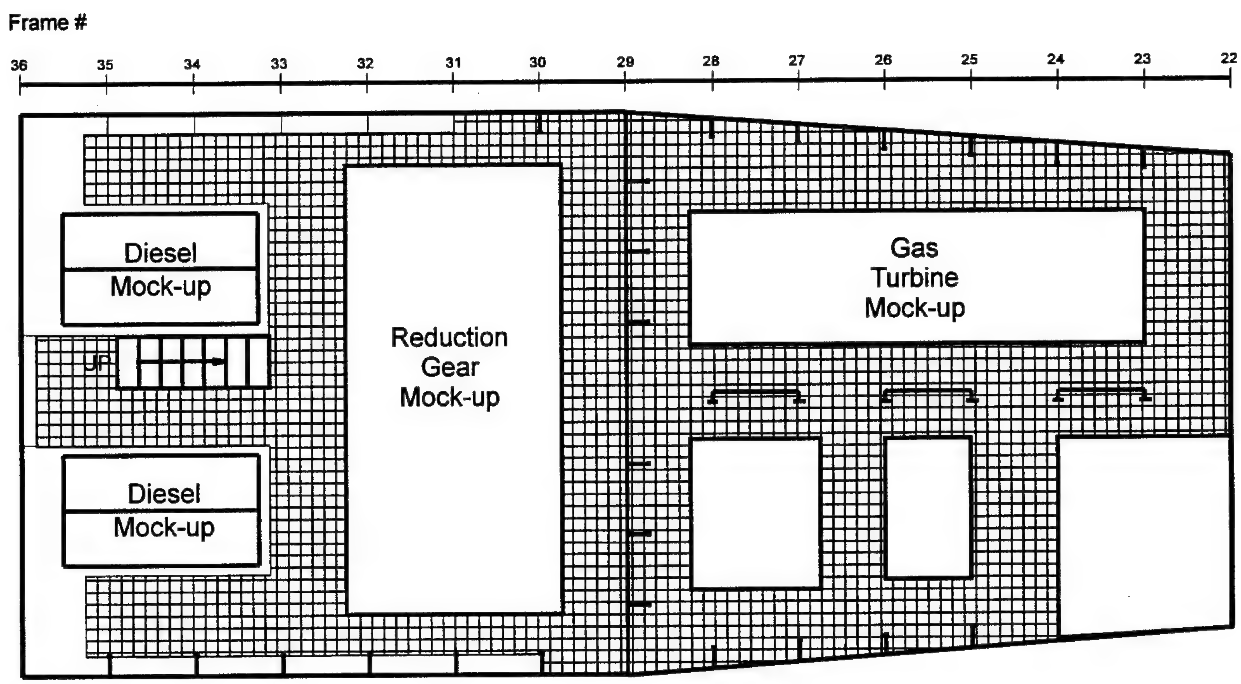
4.0 APPROACH

4.1 Test Compartment

The Phase II tests were conducted in the machinery space used during the initial phase of this investigation. The space was located in an area forward in the ship between Frames 22 and 36, and between the bilge and the third deck (Fig. 4). The space was roughly 9 x 18 x 6 m (30 x 60 x 20 ft), producing a total volume of 962 m^3 (36,000 ft^3). Included in this space was a bilge area approximately 1 m (3 ft) deep and two levels of catwalks. For the second phase of this investigation, typical machinery space equipment (i.e., engine, reduction gears, ductwork, etc.) was simulated using sheet metal mock-ups as shown in Figs. 5 and 6. The ventilation system onboard the ship was used to provide 20 air exchanges per hour, a value representative of actual machinery spaces. Both supply and exhaust fans were used to provide this ventilation. The space was instrumented for temperature, radiant, and total heat flux, optical density, and typical fire gas species (O_2, CO, and CO_2). Oxygen concentration was also measured at the base of each fire. All fires were instrumented for temperature to note extinguishment. Each test was videotaped using both a standard and an infrared video camera.



Machinery space with mock-ups - Fourth Deck



Machinery space with mock-ups - Hold Level

Fig. 4 – Machinery space deck configurations (plan views)

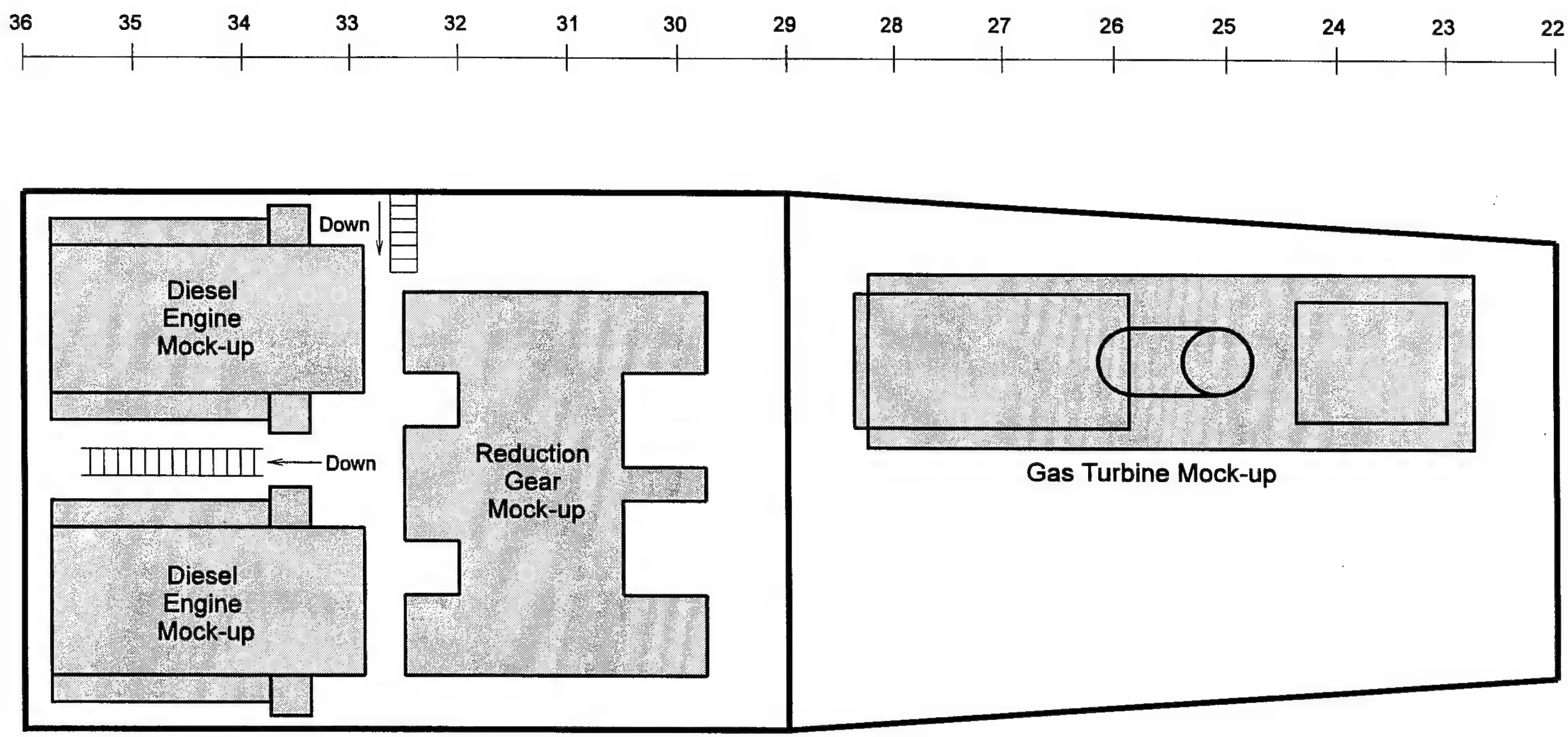


Fig. 5 – Machinery space obstructions (plan view)

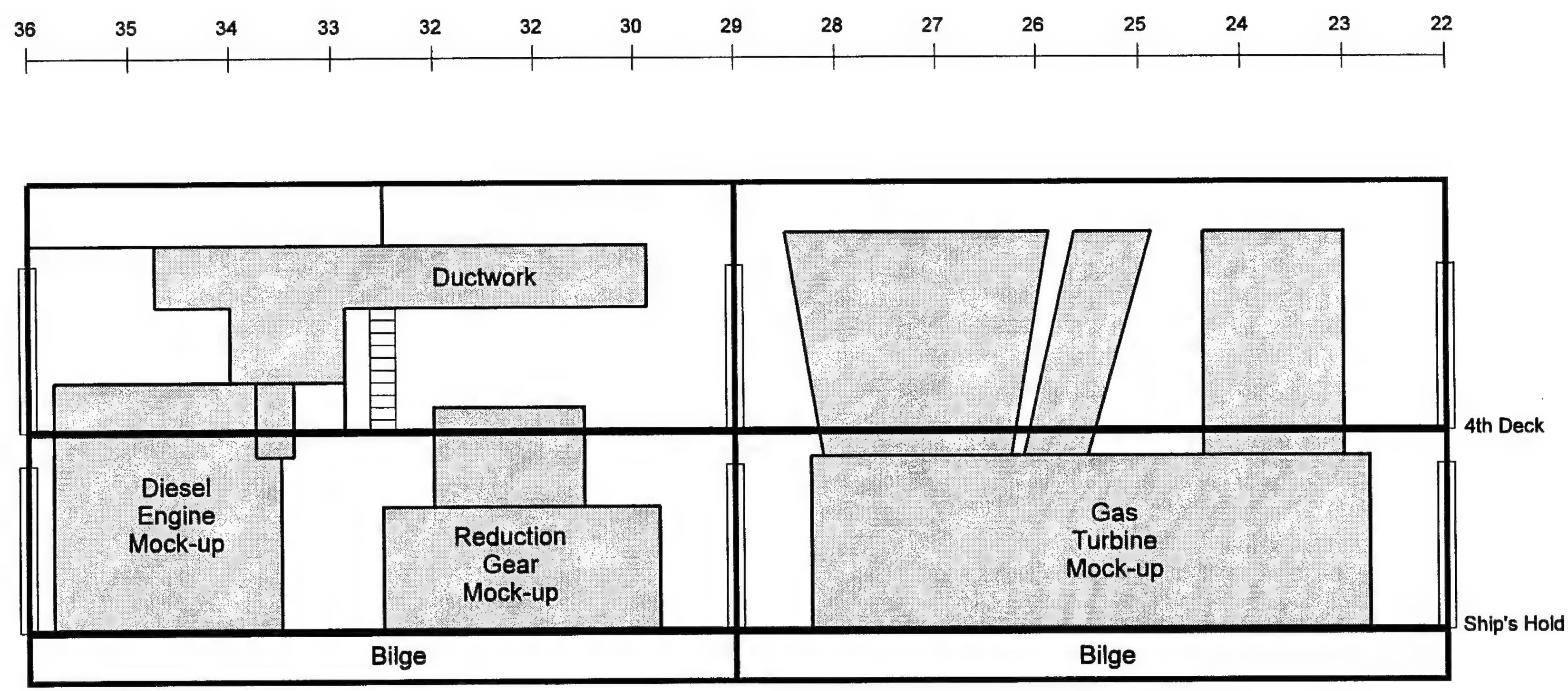


Fig. 6 – Machinery space obstructions (elevation view)

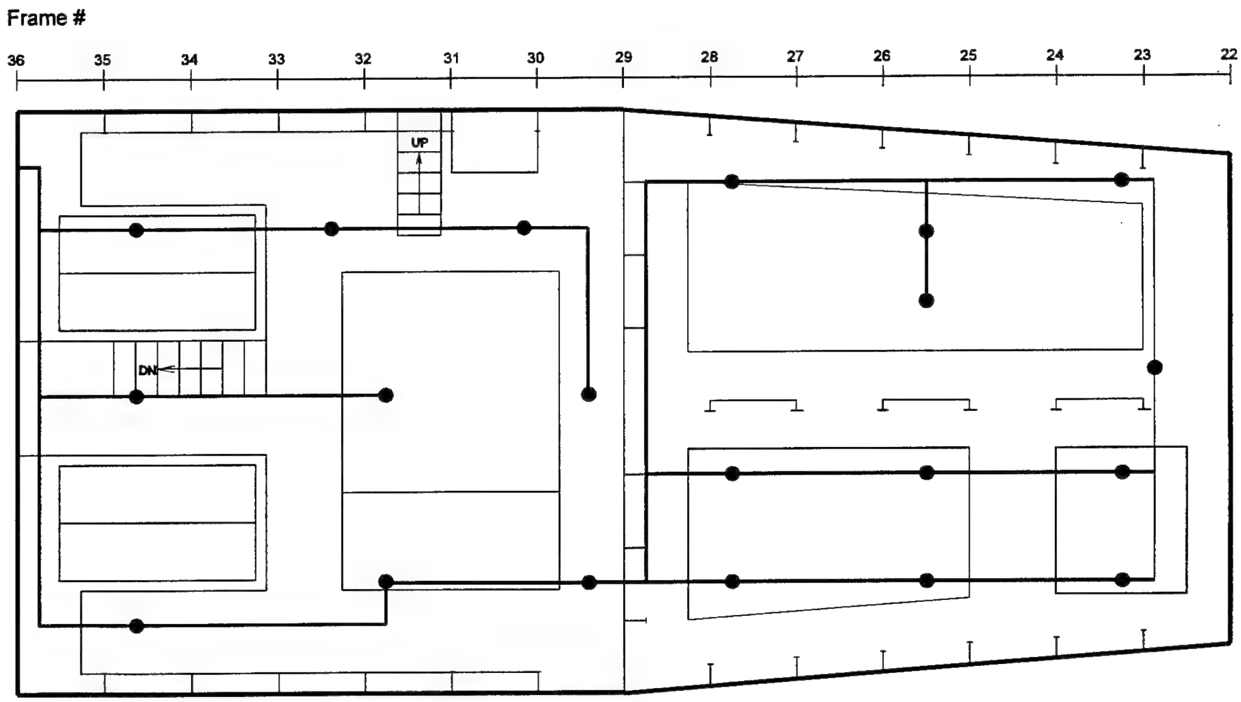
4.2 Water Mist System

During the second phase of this investigation, the nozzles were evaluated in two configurations. Initially, the nozzles were located only in the overhead of the space for comparison with the Phase I results (unobstructed machinery space). Then, a bilevel configuration was used in which the nozzles were installed at both deck levels in the space, which is similar to the way Halon systems have been installed on Navy ships. When evaluated in the single level configuration, the nozzles were installed in either of two piping networks as shown in Fig. 7. The selection between the two configurations was based on recommended nozzle spacings provided by the manufacturers. It should be noted that the nozzle locations varied between Phases I and II of this program. In the second phase, fewer nozzles were required to protect the same area due to the reduction in net compartment volume resulting from the addition of the equipment mockups. In the bilevel nozzle configuration, the nozzles were staggered between levels as shown in Fig. 8. This design was selected to minimize spray pattern interaction between the nozzles on different levels and to produce a more uniform mist distribution. All four nozzle manufacturers were evaluated in the same bilevel nozzle configuration.

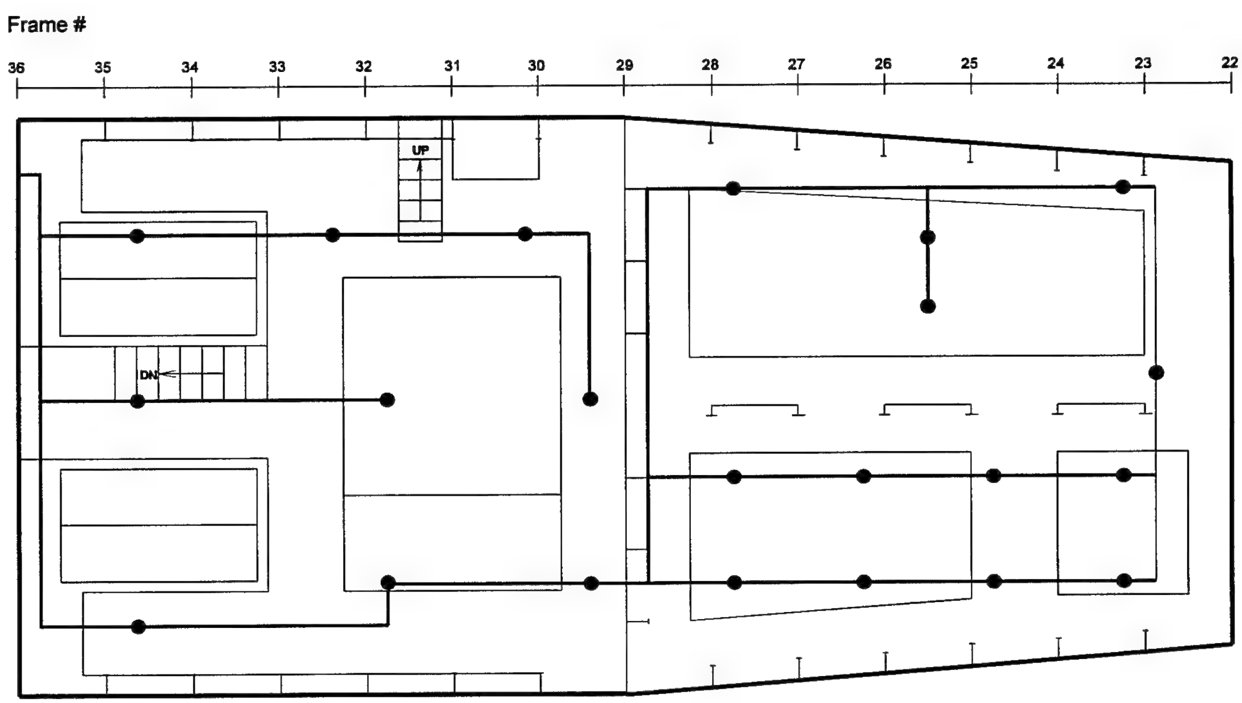
The pipe network was constructed of 2.5 cm (1 in.) stainless steel tubing (AISI 316, with a 1.65 mm (0.065 in.) wall thickness) and connected together using stainless steel single-ferrule compression fittings. Stainless steel tubing and fittings were selected to prevent rust and/or corrosion from developing inside the piping network. As installed, this system has a working pressure of 210 bar (3000 psi) and a burst pressure of 800 bar (12,000 psi). The pipe network was supplied using ten 38.0 Lpm (10 gpm), 210 bar (3000 psi) pressure washers installed in parallel (Fig. 9). Each pressure washer was equipped with a pressure regulating unloader valve allowing the pressure/flow to be adjusted to the manufacturer's design pressure/flow requirements for each system. The pumps were supplied with rain water via the fire main of the ship. The water mist system was instrumented to provide the total system flow rate and nozzle pressure for each system.

4.3 Fire Scenarios

Five of the six fire scenarios developed during the Phase I test series were selected for this evaluation. These scenarios are listed in Table 1. The locations of the fires for each scenario are shown in Fig.10. The heat release rates of these fire scenarios were estimated to be 3.5, 4.5, 6.5, and 7.5 MW. Each fire scenario consisted of a large spray fire (Fire #1, Fig. 10), a shielded spray fire (Fire #2, Fig. 10), and both a shielded and unobstructed pan fire (Fires #3 and #5, Fig. 10). Due to time constraints, the cable tray fire (Fire #4) was not used in this evaluation. The net heat release rates of the fire scenarios were varied by changing the size of the large spray fire (Fire #1). All of the above fires were produced using heptane as the fuel and were located between the ship's hold and the fourth deck. An additional test was conducted using Navy diesel fuel (F76) for the pan and spray fires to determine if diesel fuel was more or less difficult to extinguish than the test fuel heptane. Also, there were 29 small heptane pan fires (Tell Tales ~3 kW each) positioned at various locations throughout the compartment to evaluate the mist dispersion and extinguishing characteristics of the candidate systems. The first four fire scenarios were conducted with the ventilation system (both exhaust and supply) secured prior to mist system activation and the fifth with the ventilation system operating (both exhaust and supply) for the duration of the test. In all cases, the fires were allowed to preburn with the ventilation system operating for one minute prior to mist system activation.

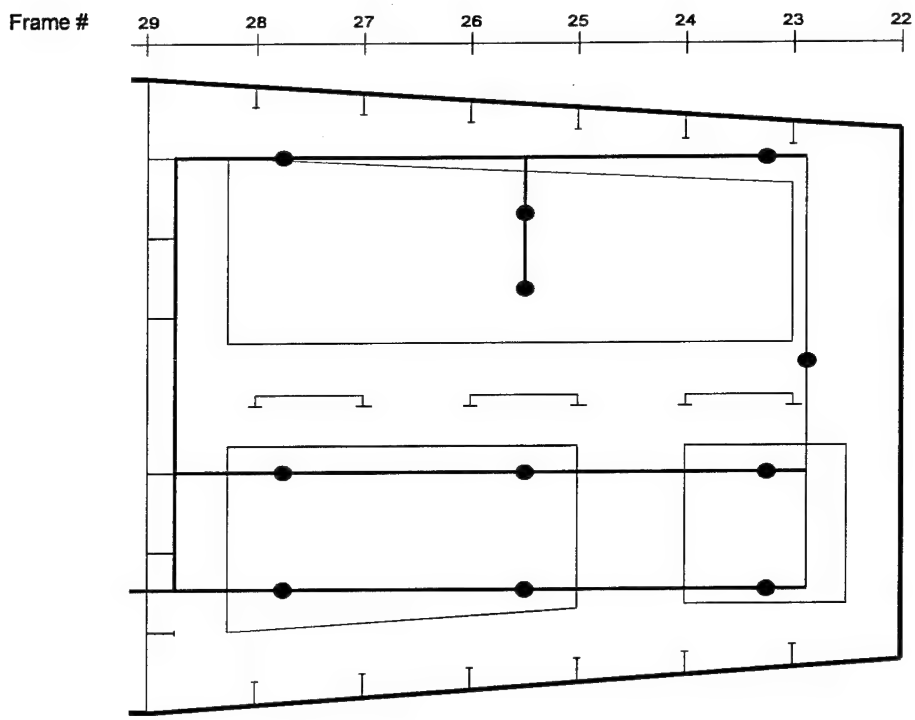


Baumac and Spraying Systems Nozzle Locations

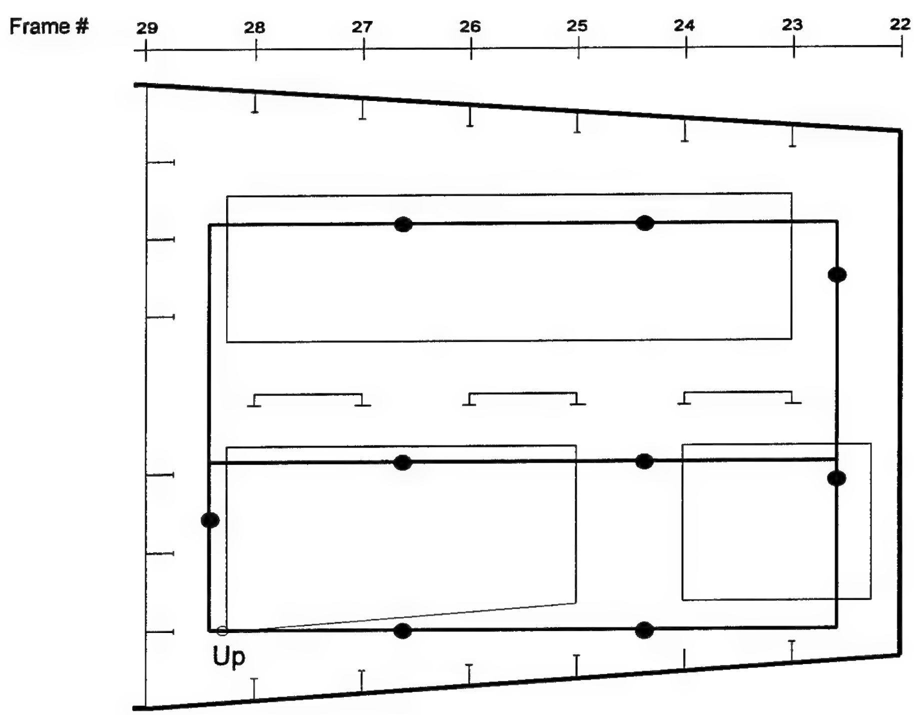


Grinnell and Marioff Nozzle Locations

Fig. 7 – Water mist system (single level configurations)



Nozzle Locations - Fourth Deck



Nozzle Locations - Ship's Hold

Fig. 8 – Water mist system (bilevel configurations)

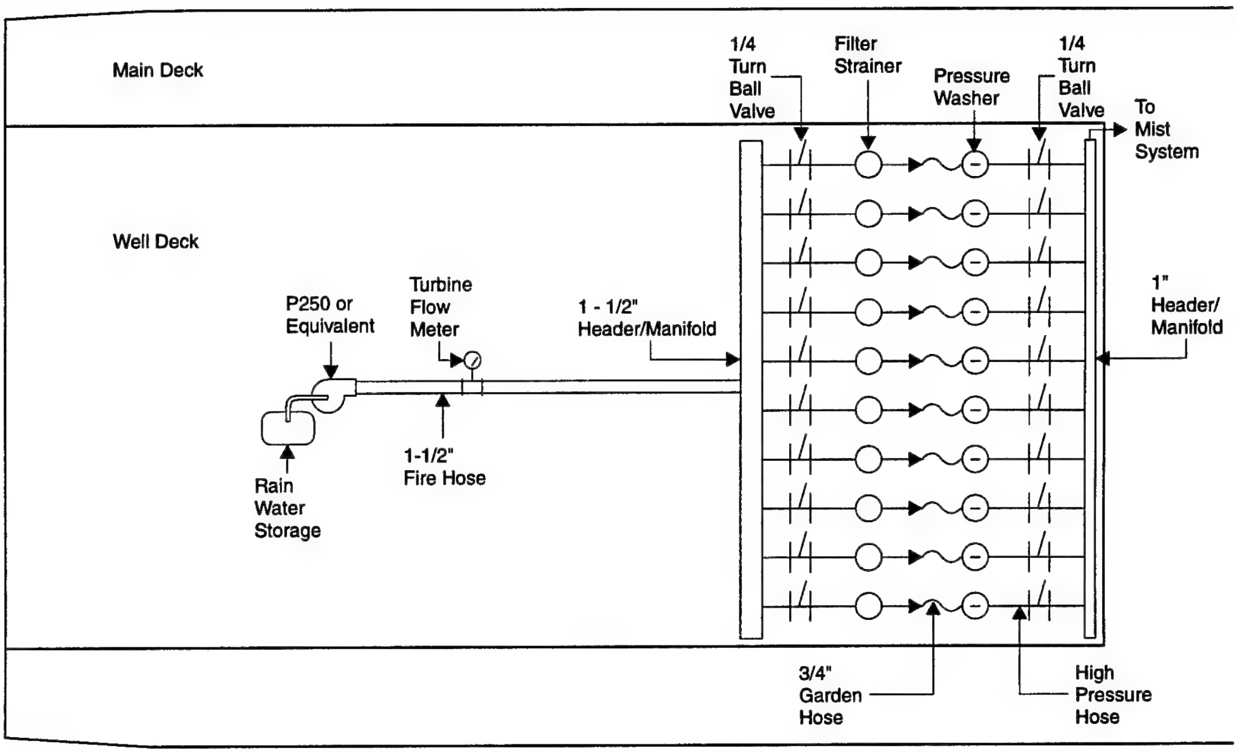
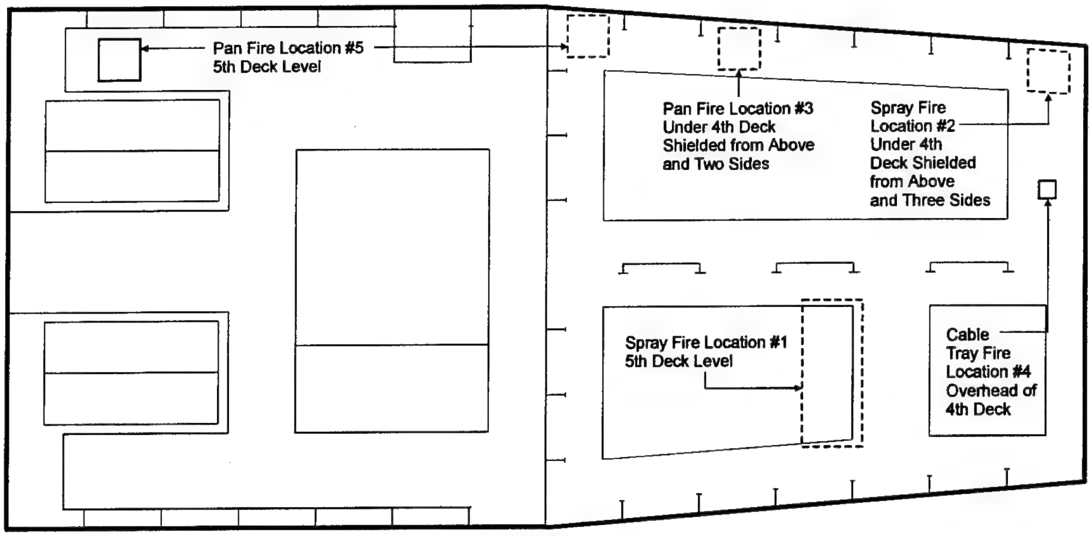
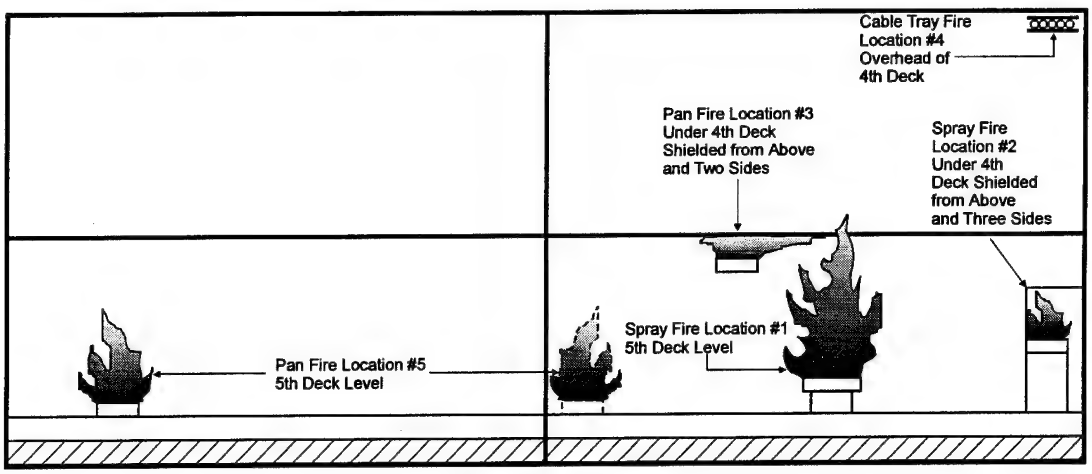


Fig. 9 – Water mist system (pump network)



Plan View



Elevation View

Fire Scenario	Ventilation	Fire #1	Fire #2	Fire #3	Fire #4	Fire #5
#1 ~ 3.5 MW	Secured	2.5 MW Spray	0.25 MW Spray	0.2 MW Pan	N/A	0.2 MW Pan
#2 ~ 4.5 MW	Secured	3.5 MW Spray	0.20 MW Spray	0.2 MW Pan	N/A	0.2 MW Pan
#3 ~ 6.5 MW	Secured	5.5 MW Spray	0.30 MW Spray	0.2 MW Pan	N/A	0.2 MW Pan
#4 ~ 7.5 MW	Secured	6.5 MW Spray	0.20 MW Spray	0.2 MW Pan	N/A	0.2 MW Pan
#5 ~ 7.5 MW	Operating	6.5 MW Spray	0.25 MW Spray	0.2 MW Pan	N/A	0.2 MW Pan

Fig. 10 – Fire locations

Table 1. Fire Scenarios

Fire Scenario	Description		
#1	~3.5 MW (Ventilation Secured)		
		Fire #1	1 - 2.5 MW spray (P-80 @ 2.8 bar (40 psi)), vertical spray
		Fire #2	1 - 0.25 MW spray (LN-8 @ 2.8 bar (40 psi)), horizontal spray
		Fires #3 & #5	2 - 0.3 x 0.3 m (1 x 1 ft) pans, 3.8 L (1 gal) of heptane in each
			29 - Tell tales with ~2.5 cm (1 in.) of heptane in each
#2	~4.5 MW (Ventilation Secured)		
		Fire #1	1 - 3.5 MW spray/pan (FF158145 @ 1.0 bar (15 psi)), horizontal spray
		Fire #2	1 - 0.15 MW spray (LN-8 @ 1.0 bar (15 psi)), horizontal spray
		Fire #3 & #5	2 - 0.3 x 0.3 m (1 x 1 ft) pans, 3.8 L (1 gal) of heptane in each
			29 - Tell tales with ~2.5 (1 in.) of heptane in each
#3	~6.5 MW (Ventilation Secured)		
		Fire #1	1 - 5.5 MW spray (P-80 @ 2.1 bar (30 psi)), vertical spray
		Fire #2	1 - 0.20 MW spray (LN-8 @ 2.1 bar (30 psi)), horizontal spray
		Fire #3 & #5	2 - 0.3 x 0.3 m (1 x 1 ft) pans, 3.8 L (1 gal) of heptane in each
			29 - Tell tales with ~2.5 cm (1 in.) of heptane in each
#4	~7.5 MW (Ventilation Secured)		
		Fire #1	1 - 6.5 MW spray (P-120 @ 4.1 bar (60 psi)), vertical spray
		Fire #2	1 - 0.30 MW spray (LN-8 @ 4.1 bar (60 psi)), horizontal spray
		Fire #3 & #5	2 - 0.3 x 0.3 m (1 x 1 ft) pans, 3.8 L (1 gal) of heptane in each
			29 - Tell tales with ~2.5 cm (1 in.) of heptane in each
#5	~7.5 MW (Ventilation Operating)		
		Fire #1	1 - 6.5 MW spray (P-120 @ 4.1 bar (60 psi)), vertical spray
		Fire #2	1 - 0.25 MW spray (LN-8 @ 4.1 bar (60 psi)), horizontal spray
		Fire #3 & #5	2 - 0.3 x 0.3 m (1 x 1 ft) pans, 3.8 L (1 gal) of heptane in each
			29 - Tell tales with ~2.5 cm (1 in.) of heptane in each

4.4 Test Procedures

The tests were initiated from the control room located on the 02 level. All key personnel were located in the control room during each test with the exception of two pump operators located in the well deck and a safety officer positioned near/outside the space. Also, two firefighters wearing protective clothing were positioned in the well deck. The water mist systems' pumps were started five minutes prior to each test. The machinery space ventilation system was activated and remained running during the initial stages (preburn) of each test. The tell tale fires were ignited two minutes prior to the start of the data acquisition system. The data acquisition system was activated one minute prior to ignition. The fires were allowed to burn freely for one minute before the ventilation system was secured and the water mist system was activated. The mist system was activated for five minutes during each test. At the completion of the five-minute discharge, the system was secured marking the termination of the test. After the test was completed, the ventilation system was activated to clear the space. Any remaining fires in the space were then either extinguished manually by the firefighting party or

allowed to burn until all of the fuel was consumed. The space remained off-limits until cleared by the safety officer and the test director.

5.0 RESULTS AND DISCUSSION

5.1 Single-level Nozzle Configuration

Fourteen tests were conducted in the simulated machinery space with the nozzles installed in the single level configuration. The extinguishment times for each of these tests are shown in Table 2. Also shown in Table 2 are the operating pressures, total system water flow rates, and the nominal water mist application rate (water flow rate per unit area) for each system. As indicated in Table 2, the extinguishment capabilities of the candidate water mist systems varied dramatically throughout these tests. The Grinnell AquaMist and modified Spraying Systems nozzles extinguished a majority of the fires during this phase of the investigation. The modified Spraying Systems nozzles consistently out-performed the other systems, not only for extinguishment times, but also for water usage requirements. For the unventilated fire scenarios (Fire Scenarios #1-4), the modified Spraying Systems nozzles extinguished all of the fires in less than two minutes using less than ~380 L (~100 gal) of water. The Grinnell AquaMist system required almost twice the time to extinguish these fires and more than three times the amount of water. As with the Phase I tests, both systems failed to extinguish the shielded spray fire (Fire #2, Fig. 10) when the ventilation system remained activated (Fire Scenario #5).

The Baumac MicroMist system was capable of extinguishing all fires in Fire Scenario #1 within six minutes of system activation. Due to the longer extinguishment times, which were attributed to a lack of spray momentum, the Baumac onsite representative decided to withdraw their system from further evaluation in the single-level configuration and proceed directly to the bilevel evaluation. The results of the bilevel tests are discussed in Section 5.2 of this report.

The Marioff machinery space nozzles were capable of extinguishing the primary fire (Fire #1, Fig. 10) considerably faster than any of the other systems evaluated in the single level configuration, but were unable to extinguish the shielded fires (both the spray fire #2 and the pan fire #3). The reason for this unusual performance was attributed to the fact that the Marioff system is designed to operate with pressurized cylinders rather than pumps. When these nozzles are supplied using pressurized cylinders, during the initial discharge of the system, the droplets produced by the system are relatively large with high momentum. These droplets are designed to penetrate the hot layer and extinguish large, unobstructed fires. Later in the discharge, nitrogen is introduced into the water stream producing substantially smaller droplets which aid in the extinguishment of obstructed/shielded fires. During these tests, the Marioff nozzles were supplied using the pumping system shown in Fig. 9. The pumps were capable of reproducing the initial stages of the discharge, but without the nitrogen, an inadequate number of small droplets were produced to extinguish the shielded fires. Accordingly, these tests may not constitute a fair representation of the capabilities of the Marioff system concept. The evaluation of the Marioff systems did, however, illustrate the need for both large and small droplets with high momentum. The larger droplets are required to penetrate the hot layer and extinguish the large fires while the smaller droplets are needed to float around the space and extinguish the small shielded fires.

Table 2. Full Scale Test Results – Simulated Machinery Space – Single Level Installation

Scenario	Extinguishment Time (min:s)			
System	Grinnell AquaMist	Baumac MicroMist	Spraying Systems	Marioff Hi-fog Machinery Space Nozzle
Nozzle Pressure	18 bar (250 psi)	103 bar (1500 psi)	105 bar (1500 psi)	105 bar (1500 psi)
System Flow Rate	310 Lpm (82 gpm)	246 Lpm (65 gpm)	166 Lpm (44 gpm)	257 Lpm (68 gpm)
Application Rate	1.86 Lpm/m^2 (0.046 gpm/ft^2)	1.46 Lpm/m^2 (0.036 gpm/ft^2)	1.01 Lpm/m^2 (0.025 gpm/ft^2)	1.54 Lpm/m^2 (0.038 gpm/ft^2)
Scenario #1 (3.5 MW)*				
Fire #1	3:45	4:22	1:45	
Fire #2	4:20	5:38	0:50	
Fire #3	1:25	2:53	0:55	
Fire #5	3:25	4:28	1:40	
Tell Tales***	29/29	29/29	29/29	
Scenario #2 (4.5 MW)*				
Fire #1	3:30		1:45	0:32
Fire #2	4:00		1:27	No
Fire #3	0:50		0:40	No
Fire #5	2:05		1:30	1:30
Tell Tales***	29/29		29/29	27/29
Scenario #3 (6.5 MW)*				
Fire #1	2:45		1:00	
Fire #2	3:30		1:00	
Fire #3	0:35		0:30	
Fire #5	2:33		1:20	
Tell Tales***	29/29		29/29	
Scenario #4 (7.5 MW)*				
Fire #1	1:40		1:20	0:34
Fire #2	2:25		1:25	No
Fire #3	0:20		0:50	No
Fire #5	0:55		1:15	0:46
Tell Tales***	29/29		29/29	27/29
Scenario #5 (7.5 MW)**				
Fire #1	3:41		2:30	0:38
Fire #2	No		No	No
Fire #3	0:55		0:20	No
Fire #5	No		1:15	4:00
Tell Tales***	28/29		28/29	24/29

* Ventilation (exhaust and supply) was secured during mist system activation.
** Ventilation (exhaust and supply) remained operating during this test.
*** Number of tell tales extinguished / number of tell tales in the scenario.

5.1.1 <u>Comparison between Empty versus Simulated Machinery Space Results</u>

The extinguishment times recorded for the tests conducted in both the empty machinery space (Phase I) and the simulated machinery space (Phase II) are shown in Table 3 for the single level installation. As illustrated in this table, the extinguishment times observed in the simulated machinery space are less than those observed in the empty space. Although these results were somewhat unexpected, there are many factors that could contribute to this increase in performance. Modifications made to the candidate systems between Phases I and II of this investigation may have contributed to the faster extinguishment times. However, the more likely explanation is the reduction in net volume of the space resulting from the addition of the equipment mockups. The reduced volume corresponds to less oxygen available for the fire, which means that the oxygen concentration will decrease faster in the simulated space than in the empty compartment for a given fire size. The overall surface area of the space is also increased due to the addition of the mockups. This increased surface area will tend to decrease the mist concentration due to higher plate losses (water droplets impacting on the surfaces). However, if these surfaces have been heated by the fire, as the mist plates out on the surface, steam will be produced, which may help smother the fire due to oxygen dilution.

In general, with the nozzles installed in the single level configuration, the extinguishment times ranged from approximately 1.5 to 6.0 minutes independent of the compartment configuration (empty or simulated with equipment mockups). These lengthy extinguishment times suggest that oxygen depletion, resulting from the consumption of oxygen by the fire and potentially from the displacement of oxygen due to the expansion of the mist to steam, significantly contributed to the extinguishment of these fires. As observed during the Phase I tests, the oxygen concentration in the space was measured to drop to almost 14 percent for the tests with the longer extinguishment times (4-5 minutes). Future systems need to rely more on gas-phase cooling than on oxygen depletion in order to shorten the time required to extinguish the fire to minimize damage. Some of the potential solutions to this problem are increased water flow rates, increased spray momentum, and water mist system designs that have better mist dispersion characteristics (i.e., multiple level nozzles and tighter nozzle spacings).

5.2 Bilevel Nozzle Configuration

Twelve tests were conducted in the simulated machinery space with the nozzles installed at two levels (just below the third and fourth deck levels). The extinguishment times for each test are listed in Table 4. Also shown in Table 4 are the operating pressures, total system water flow rates, and the nominal water mist application rates (water flow rate per unit area) for each system. As observed in the previous tests, the modified Spraying Systems nozzles demonstrated superior capabilities not only with respect to extinguishment times, but also for water usage requirements (overall efficiency). In the bilevel configuration, the modified Spraying Systems nozzles were capable of extinguishing all of the fires in the unventilated tests within 25 seconds of the mist system activation using less than 100 L (25 gallons) of water. During the ventilated test (Fire Scenario #5), the system extinguished three of the four fires within 50 seconds of the mist system activation. As observed in previous tests, the system was unable to extinguishing the obstructed spray fire located in front of the supply vent. This shielded spray fire (Fire #2, Figure 10) in Fire Scenario #5 was not extinguished by any of the systems evaluated in this investigation. The remaining three systems each produced varying results. The Grinnell AquaMist system failed to extinguish all of the small fires independent of the ventilation conditions in the space. The Baumac MicroMist system was unable to extinguish

the two pan fires while the Marioff Hi-fog system (cabin nozzles) failed to extinguish the two shielded fires.

Table 3. Full Scale Test Results – Empty (Phase I) vs. Simulated (Phase II) Machinery Space Configurations – Single Level Installation

Scenario	Extinguishment Time (min:s)					
System	Grinnell AquaMist		Baumac MicroMist		Spraying Systems	
Nozzle Pressure	18 bar (250 psi)		105 bar (1500 psi)		105 bar (1500 psi)	
System Flow Rate	310 Lpm (82 gpm)		246 Lpm (65 gpm)		166 Lpm (44 gpm)	
Application Rate	1.86 Lpm/m^2 (0.046 gpm/ft^2)		1.46 Lpm/m^2 (0.036 gpm/ft^2)		1.01 Lpm/m^2 (0.025 gpm/ft^2)	
Space Configuration	simulated	empty	simulated	empty	simulated	empty
Scenario #1 (3.5 MW)*						
Fire #1	3:45	4:15	4:22	6:00	1:45	2:30
Fire #2	4:20	No	5:38	No	0:50	1:45
Fire #3	1:25	3:15	2:53	4:30	0:55	2:30
Fire #5	3:25	2:20	4:28	3:30	1:40	2:15
Scenario #2 (4.5 MW)*						
Fire #1	3:30	2:45		3:30	1:45	2:00
Fire #2	4:00	2:50		0:47	1:27	1:15
Fire #3	0:50	1:45		No	0:40	1:30
Fire #5	2:05	2:15		No	1:30	2:15
Scenario #3 (6.5 MW)*						
Fire #1	2:45	4:30		3:30	1:00	2:15
Fire #2	3:30	No		No	1:00	1:15
Fire #3	0:35	2:30		2:30	0:30	1:30
Fire #5	2:33	3:00		2:30	1:20	2:00
Scenario #4 (7.5 MW)*						
Fire #1	1:40	2:05		2:30	1:20	1:30
Fire #2	2:25	1:02		No	1:25	1:00
Fire #3	0:20	1:12		1:40	0:50	0:45
Fire #5	0:55	No		1:15	1:15	1:00
Scenario #5 (7.5 MW)**						
Fire #1	3:41	3:40		4:00	2:30	3:45
Fire #2	No	No		No	No	No
Fire #3	0:55	1:45		1:45	0:20	No
Fire #5	No	1:45		3:20	1:15	2:00

* Ventilation (exhaust and supply) was secured during mist system activation.
** Ventilation (exhaust and supply) remained operating during this test.

Table 4. Full Scale Test Results – Simulated Machinery Space – Bilevel Installation

Scenario	Extinguishment Time (min:s)			
System	Grinnell AquaMist	Baumac MicroMist	Spraying Systems	Marioff Hi-fog cabin nozzle
Nozzle Pressure	18 bar (250 psi)	105 bar (1500 psi)	105 bar (1500 psi)	105 bar (1500 psi)
System Flow Rate	310 Lpm (82 gpm)	246 Lpm (65 gpm)	166 Lpm (44 gpm)	257 Lpm (68 psi)
Application Rate	3.69 Lpm/m^2 (0.091 gpm/ft^2)	2.92 Lpm/m^2 (0.072 gpm/ft^2)	2.03 Lpm/m^2 (0.050 gpm/ft^2)	3.08 Lpm/m^2 (0.076 gpm/ft^2)
Scenario #2 (4.5 MW)*				
Fire #1	1:18	0:36	0:20	0:22
Fire #2	0:41	0:47	0:20	0:46
Fire #3	No	No	0:20	No
Fire #5	No	No	0:20	1:07
Tell Tales***	15/15	15/15	15/15	14/15
Scenario #4 (7.5 MW)*				
Fire #1	2:05	0:32	0:20	0:27
Fire #2	1:02	0:34	0:15	0:35
Fire #3	1:12	No	0:20	No
Fire #5	No	No	0:25	1:05
Tell Tales***	15/15	15/15	15/15	15/15
Scenario #5 (7.5 MW)**				
Fire #1	No	1:15	0:40	1:46
Fire #2	No	No	No	No
Fire #3	No	No	0:40	No
Fire #5	2:40	No	0:50	No
Tell Tales***	14/15	13/15	14/15	14/15

* Ventilation (exhaust and supply) was secured during mist system activation.
** Ventilation (exhaust and supply) remained operating during this test.
*** Number of tell tales extinguished/number of tell tales in scenario.

5.3 Single versus Bilevel Nozzle Configuration

A comparison of the results produced by the single and bilevel system configurations is shown in Table 5. The sole impact of varying the system design (single versus multilevel) cannot be determined since the application rate doubled when the nozzles were installed on two levels. Intuitively, the extinguishment times for these fires should dramatically decrease for two obvious reasons: increased water flow rate/application rate and better mixing characteristics due to the increased number of nozzles installed in the space. This anticipated decrease in extinguishment times was observed for the modified Spraying Systems nozzles, but not for the Grinnell AquaMist system, where a number of fires were not extinguished in the bilevel tests. The capabilities of the Grinnell AquaMist system were actually observed to

decrease in the bilevel configuration. In this configuration, the Grinnell AquaMist nozzles produced sporatic results against the large fire (Fire #1), an increase in performance against the shielded spray fire (Fire #2), and a decrease in performance against the two pan fires (Fires #3 and #5). For the Grinnell AquaMist systems, the lower level of nozzles appears to alter the dispersion of the mist throughout the compartment in such a way that the mist is redirected away from the pan fire locations. The modified Spraying Systems nozzles exhibited a significant increase in performance with the extinguishment times reduced by a factor of 5 for the bilevel configuration. The Spraying Systems nozzles were capable of extinguishing all fires within 25 seconds of system activation, which is similar to the performance of the gaseous halon alternatives. The dependency on oxygen depletion to aid in extinguishment was also reduced by the addition of the lower level of nozzles (better mist dispersion characteristics and higher water/mist flow rates). With the modified Spraying Systems nozzles installed in the bilevel configuration, the oxygen concentrations in the space during extinguishment were observed to remain above 19 percent. This compares to 14 percent for the single level configuration.

Table 5. Full Scale Test Results – Single Level vs. Bilevel Installation

Scenario	Extinguishment Time (min:s)			
System	Grinnell AquaMist		Spraying Systems	
Nozzle Pressure	18 bar (250 psi)	18 bar (250 psi)	105 bar (1500 psi)	105 bar (1500 psi)
System Flow Rate	310 Lpm (82 gpm)	310 Lpm (82 gpm)	166 Lpm (44 gpm)	166 Lpm (44 gpm)
Application Rate	1.86 Lpm/m^2 (0.046 gpm/ft^2)	3.69 Lpm/m^2 (0.091 gpm/ft^2)	1.01 Lpm/m^2 (0.025 gpm/ft^2)	2.03 Lpm/m^2 (0.050 gpm/ft^2)
Nozzle Location	single level	bilevel	single level	bilevel
Scenario #2 (4.5 MW)*				
Fire #1	3:30	1:18	1:45	0:20
Fire #2	4:00	0:41	1:27	0:20
Fire #3	0:50	No	0:40	0:20
Fire #5	2:05	No	1:30	0:20
Scenario #4 (7.5 MW)*				
Fire #1	1:40	2:05	1:20	0:20
Fire #2	2:25	1:02	1:25	0:15
Fire #3	0:20	1:12	0:50	0:20
Fire #5	0:55	No	1:15	0:25
Scenario #5 (7.5 MW)**				
Fire #1	3:41	No	2:30	0:40
Fire #2	No	No	No	No
Fire #3	0:55	No	0:20	0:40
Fire #5	No	2:40	1:15	0:50

* Ventilation (exhaust and supply) was secured during mist system activation.
** Ventilation (exhaust and supply) remained operating during this test.

5.4 General

5.4.1 Fuel Comparison

A test was also conducted using Navy diesel fuel (F-76, flash point 60°C (140°F)) to verify that the lower flash point test fuel (Heptane, flash point –4°C (25°F)) represents a worst case scenario and that data collected throughout this investigation are somewhat conservative. The comparison test selected was the large, unventilated fire scenario (Scenario #4, 7.5 MW). This test was conducted using the modified Spraying Systems nozzles installed in the bilevel configuration. During this test, the four primary fires were produced using F76 while the tell-tale fires were still fueled with heptane. F76 was not used in the tell tales due to anticipated problems with ignition. The results of these tests are listed in Table 6. As shown in Table 6, the higher flash point fuel, F76, was extinguished almost twice as fast as the heptane fire scenarios. This suggests that the lower flash point fuel is clearly a worst case scenario. During the evaluation of F76, the visibility in the space was observed to significantly increase after the activation of the water mist system. This suggests that the dense black smoke produced by the F76 fuel was being removed from the plume and the hot layer by the water mist.

Table 6. Fuel Comparison Tests

Scenario	Extinguishment Time (min:sec)	
System	Spraying Systems	
Nozzle Pressure	105 bar (1500 psi)	105 bar (1500 psi)
System Flow Rate	164 Lpm (44 gpm)	164 Lpm (44 gpm)
Application Rate	2.03 Lpm/m^2 (0.05 gpm/ft^2)	2.03 Lpm/m^2 (0.05 gpm/ft^2)
Fuel	Heptane	F76
Scenario #4 (7.5 MW)*		
6.5 MW Spray	0:20	0:11
300 kW Spray (Shielded)	0:15	0:11
250 kW Pan (Shielded)	0:20	0:12
250 kW Pan	0:25	0:12
Tell Tales	15/15	15/15

* Ventilation (exhaust and supply) was secured during mist system activation.

5.4.2 Tenability

One of the perceived advantages of using water mist as a Halon alternative is the rapid cooling produced during the discharge of the mist. During Phase I of this program, the compartment temperatures were observed to rapidly approach ambient conditions about 30 seconds after mist discharge [3]. This discovery, along with a thorough review of the thermal conditions measured in the space, prompted the firefighting party wearing protective clothing and emergency breathing devices (EBDs) to enter the space immediately after the mist system was activated. The firefighting party reported that the conditions in the space were extremely

hot and humid but still tenable. As the test series continued and the firefighting party became more familiar with the conditions in the space, less thermally protective clothing was substituted for the standard Navy dress and equipment. The firefighting party also varied their approach and position in and around the space throughout these tests. By the end of the test series, the firefighting party remained in the space for the entire duration of the test dressed in standard Navy cotton coveralls and equipped with emergency breathing devices (EBDs). The only two adverse effects noted by the firefighting party were a change in compartment pressure during the initial discharge of the water mist system (which may have been caused by rapid steam expansion or cooling of the hot gases in the compartment) and an obvious reduction in visibility. The pressure pulse caused the firefighters' ears to pop. However, an inspection of the pressure data measured in the compartment showed an insignificant, almost immeasurable pressure buildup in the space during the test.

Observations solicited from the firefighting party pertaining to visibility suggest that under worst case conditions, one could still see the hand rail approximately 1 m (3 ft) in front of them and that light sources (i.e., lights, fires, etc.) could be seen for greater distances. It should be noted again that during Phase I of this test program, it was determined that the Navy's handheld thermal imager (NFTI) was capable of seeing through the mist.

5.4.3 Protection Against Reignition

An evaluation was also conducted to determine the protection against reignition provided by the water mist. This evaluation was conducted by trying to reignite the 3.5 MW pan/spray fire (Fire #1, Scenario #2) both during and immediately after mist system discharge. The attempt to reignite the spray was initially conducted using a spark ignition system. Due to wetting/electrical shorting problems, the spark ignitor was abandoned for manual reignition using a torch. Two attempts at reignition were conducted with the mist system remaining activated. During the first attempt, the torch was extinguished before reaching the fuel spray. During the second attempt, less than 5 percent of the spray ignited briefly before both the torch and the spray were extinguished. This demonstrates the potential inerting capabilities of the mist system when the system remains activated. During the attempt at reignition with the mist system secured, the spray ignited immediately, as if no mist were present, confirming that the residual mist in the space provides little if any reflash protection.

5.4.4 Class A Fire Tests

An additional test was conducted against a large wood crib to evaluate the ability of a water mist system to extinguish a large, deep-seated Class A fire. The crib was constructed of oak members having nominal cross sections of 5 cm x 5 cm (2 in. x 2 in.). The overall wood crib dimensions were approximately 1.2 x 1.2 x 0.7 m (4 x 4 x 2.5 ft). The crib was placed at Fire Location #1 (Fig. 10) and allowed a five-minute preburn prior to mist system activation. During this test, the mist system was activated for three minutes and then secured. After the three-minute discharge, no flames were visible above the crib, but substantial glowing areas were observed deep in the center of the crib. At this point, the crib was extinguished using a handline by the firefighting party. If the mist system had been activated for a longer duration, it is possible that the wood crib may have been completely extinguished. It is also assumed that after the initial three-minute discharge and the system was secured, the crib would have slowly redeveloped into a fully involved wood crib fire.

6.0 CONCLUSIONS

In general, the fire extinguishing capabilities of the candidate water mist systems were improved by the addition of equipment mockups in the machinery space. The increase in system performance was attributed to a decrease in net volume in the space which results in a faster oxygen depletion rate for a given size fire in a closed compartment. The modified Spraying Systems nozzles consistently demonstrated superior fire extinguishment capabilities throughout this evaluation. The firefighting capabilities of this system were also significantly improved by installing the nozzles at two elevations in the space. In this configuration, the system was capable of extinguishing all of the unventilated fires in less than 25 second of system activation and in the process used less than 100 L (25 gal) of water. Based on these capabilities, this nozzle was selected for future water mist system development for Navy machinery space applications.

While these results are very encouraging, it is recognized that future research into the mist dispersion characteristics of the system as well as flame interaction is needed to better understand the capabilities and limitations of the system. This information will also aid in the development of a design criteria for typical Navy machinery space applications on new ships starting with the LPD-17.

7.0 REFERENCES

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